Soil compaction in Northern Italian vineyards: challenges and mitigation strategies

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Abstract

Soil compaction presents significant challenges for perennial crops, which occupy the same land for many years. The practice of arranging plants in rows and the frequent use of heavy machinery is leading to soil compaction and rut formation. A study conducted in espaliers vineyards in Northern Italy (Oltrepò, Lombardy region) examined the effects of grass-covered versus tilled inter-rows and the influence of mechanical versus manual harvesting. The study was based on a series of penetrometer resistance measurements conducted throughout the entire growing season. Early-season measurements revealed values exceeding 4 MPa, surpassing the 1-3 MPa threshold identified in the literature as a limit for root growth, grape quality, and susceptibility to pathogens. The negative impact of soil compaction was not limited to the ruts formed by agricultural machinery but also affected adjacent areas. The well-documented regeneration of agricultural soil structure during the cold season was in these cases inadequate to alleviate the significant compaction observed. Furthermore, mechanical harvesting, particularly in wet conditions, significantly exacerbated soil compaction, with measurements indicating nearly 5 MPa in ruts. These findings underscore the imperative for implementing strategies aimed at mitigating the adverse impacts of soil compaction on vine health and the sustainability of vineyards.

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Introduction

Soil compaction is a widely acknowledged process of soil degradation, predominantly affecting mechanical properties as documented in literature (Ferree and Streeter, 2004; Lagacherie *et al*., 2006; Nawaz *et al*., 2013; Ferianc *et al*., 2016). The degree of compaction is intricately associated with soil texture, water content, and organic matter levels (Linares *et al*., 2014; Polge de Combret-Champart *et al*., 2013; Ferrero *et al*., 2005; Jakšić *et al*., 2021; Liebhard *et al*., 2024). Both tillage practices and persistent machinery traffic are pivotal factors influencing soil stability and the dynamics of compaction (Arnaez *et al*., 2007; Martínez-Casasnovas and Concepcion Ramos, 2009; Kvaternjak *et al*., 2012; Špoljar *et al*., 2014; Biddoccu *et al*., 2016; Bogunovic *et al*., 2016; Bogunovic *et al*., 2017, Rodrigo-Comino, 2018; Capello *et al*., 2019, Capello *et al*., 2020). Concerning soil texture, compaction in sandy soils demonstrates a rapid escalation with low intensity, whereas in clayey and silty soils, the compaction process advances gradually but can reach high levels of intensity (Lamandé and Schjønning, 2011).

Elevated soil compaction has deleterious effects on crop water availability, solute concentrations, and air distribution, thereby disrupting the soil equilibrium and impeding nutrient accessibility for plants, as documented in previous studies (Ferree and Streeter, 2004; Lanyon *et al*., 2004; Lazcano *et al*., 2020; Napoli *et al*., 2017; Nawaz *et al*., 2013, Visconti *et al*., 2024). The reduction in pore dimensions associated with compaction not only signifies a decline in oxygen levels within the soil but also has the potential to increase the production of greenhouse gases, as indicated by relevant research findings (Ferianc *et al*., 2016).

Based on the use of a micro-penetrometer, Wang *et al*. (2016) provide insights of significant influence of wetting-drying (W-D) cycles on soil hydro-mechanical behaviour, resulting in consequential modifications to soil structure. In particular, they studied the temporal–spatial evolution of soil strength by analysing the obtained penetration curves to characterize the effect of W-D cycles on soil mechanical behaviour. Importantly, fluctuations in soil moisture levels across different seasons, particularly influenced by heavy machinery traffic, hold the potential to disrupt the typical behaviour of soil agglomerates, thereby augmenting penetration resistance (Lamandé and Schjønning, 2011).

The adverse effects of soil compaction are further manifested in cultivars where root growth is impeded by soil resistance, resulting in diminished budding and a reduced leaf surface area, ultimately leading to decreased photosynthesis, as substantiated by existing literature (Ferree and Streeter, 2004; Morlat and Jacquet, 2003; Nawaz *et al*., 2013; Wheaton *et al*., 2008). A comprehensive understanding of soil behaviour is crucial for precise predictions of the enduring impacts of soil compaction on diverse crops, thereby facilitating the development of forecasting models (Schneider *et al*., 2020). It is noteworthy that each crop displays a distinct tolerance to the effects of soil compaction, a trait that can be modified through selective breeding practices and/or appropriate soil tillage strategies, such as for example periodical chiselling or subsoiling. The improvement of topsoil structure through periodic tillage is generally rows, especially within the ruts formed by the tyres or tracks of the machinery (Kvaternjak *et al*, 2012; Špoljar *et al*., 2014). Vineyards adhere to a long-term planting scheme that may endure for decades, allowing for the comprehensive investigation of the effects of machinery traffic in the inter-row areas. These studies contribute valuable insights into the dynamics of soil compaction over various growing seasons and in diverse field locations (Lanyon *et al*., 2004).

Moreover, an inappropriate combination of soil tillage and machinery traffic has the potential to exacerbate the situation. Bogunovich *et al*. (2016, 2017) conducted a comparative analysis of two vineyards of varying ages to investigate the correlation between soil compaction and some distinct management systems, including no-tillage, conventional tillage and yearly inversed grass covered, by measuring bulk density, penetration resistance, soil water content and CO_2 fluxes. The findings revealed reduced soil resistance up to a depth of 0.4 m in tilled inter-row positions as a direct consequence of tillage, in comparison to those covered with grass. Nonetheless, soil compaction undeniably exerts an impact on plant growth, leading to diminished sprout growth, reduced leaf surface, smaller branch dimensions, lower bunch sugar content, decreased photosynthetic activity and ultimately reduced yields, as documented in pertinent literature (Ferree and Streeter, 2004; Lanyon *et al*., 2004).

Values derived from penetrometer measurements serve as indicators of the resistance roots encounter during their growth (Davies *et al*., 2018). In an extensive multi-year investigation, Burg *et al*. (2012) utilized penetrometer resistance tests to evaluate the impact of machinery traffic in vineyards on various inter-row surfaces, including both grassed areas and those periodically subjected to deep tillage. The results demonstrate a reduction in penetration resistance within grassed inter-rows; however, critical values are surpassed as shallow as a depth of 0.2 m. The annual assessment of soil compaction highlights a more pronounced escalation, notably discernible starting from the third year of the analysis. This paper was developed to elucidate the temporal evolution of soil compaction throughout the growing season in three vineyards located in Northern Italy. The primary objective was to determine whether, under the investigated conditions, soil compaction reaches or exceeds values deemed critical in the literature at certain stages of the vegetative phases. This assessment is crucial with regard to root growth, vegetation and fruit development and, most importantly, the overall health status of the plants. The analysis encompasses considerations such as the sampling period, the spatial distribution of sampling points, penetration depth, machinery traffic and characteristics of soil surface management.

Materials and Methods

The tests were conducted at a winery situated in the Oltrepò district, entirely within the municipality of San Damiano al Colle, province of Pavia (Lombardy, Italy), at coordinates 45.02769 N latitude and 9.34869 E longitude, with an average altitude above sea level of 174 m (Figure 1).

The vineyard encompasses grape varieties such as Bonarda, Barbera, Croatina, Pinot, and Riesling, boasting an average vine age of approximately 25-30 years. The analyzed vineyards display variations in soil texture, soil management techniques, and mechanization approaches. To offer a more detailed overview:

Vineyard «Bosco»: encompassing an area of approximately 4 ha, this vineyard features Barbera vines arranged with a planting

Figure 1. Locations on the map of the examined vineyards.

configuration of 0.80 m on the row and 2.20 m between rows. Multiple soil samples were meticulously collected at depths of 10 and 30 cm for each plot, blended and subsequently analyzed. The soil texture comprises 22% sand, 51% silt, and 27% clay (classified as loamy-silty soil), with a total limestone content of 30% and an organic matter content of 1%. The vineyard has consistently maintained a grassy surface for several years, and manual harvesting is employed. For seasonal operations, a narrow-track 4WD tractor with a total mass of 2,800 kg was used, equipped with 280/70 R16 front tyres and 420/70 R24 rear tyres. This tractor is coupled with a trailed sprayer for plant protection products (PPP) distribution having an overall mass of 2100 kg at full load, and a shredder weighing 600 kg, connected to the 3-point hitch, for grass mowing. The sprayer was equipped with a couple of tyres 205/60 R 14.

Vineyard «Bosco Rovati»: this small plot, adjacent to the Bosco vineyard, shares identical vine varieties and planting configurations, as well as similar soil texture. However, the management approach for this vineyard involves the use of a crawler tractor with a total mass of 4370 kg, equipped with two steel tracks measuring 310 mm in width, providing a total contact area of nearly 10,000 cm². The topsoil in this vineyard is subjected to alternate row management, incorporating both tillage (up to a depth of 20 cm using a cultivator) and the presence of a grass cover.

Vineyard «San Michele»: situated in close proximity to the farm centre, this vineyard covers an area of approximately 4.25 ha, featuring planting configurations identical to the aforementioned vineyards, with Barbera and Pinot Nero vines. The soil texture consists of 24% sand, 38.7% silt, and 37.3% clay (classified as loamy-clayey soil), accompanied by a total limestone content of 26% and approximately 1.4% organic matter. This vineyard is managed with a permanent grass cover and mechanical harvesting is employed. Similar to the Bosco vineyard, seasonal operations in this vineyard utilize a narrow-track tractor. Mechanical harvesting is carried out using the same crawler tractor employed in the Bosco Rovati vineyard, connected to a trailed grape harvester equipped with a couple of tyres 405/70 R 20, with a mass of 3700 kg at full load.

The compaction measurements were conducted in four periods throughout the entire growing season. The first test campaign was conducted in early spring (mid-April), preceding any machinery operations in the vineyard. The purpose was to evaluate soil compaction after the winter hiatus for subsequent comparison with soil conditions during the growing season. The second set of measurements took place in early summer (beginning of July) following the completion of the majority of PPP treatments. Subsequently, the last two campaigns occurred at the end of summer (mid-September) and early autumn (beginning of October), respectively, before and after the harvesting period. Compaction samples were collected at the centre of the inter-row, within the row and in both ruts created by machinery traffic (Table 1).

In each campaign, a minimum of 50 penetrations were performed for each test condition, reaching a maximum depth of 0.6 m. For each investigated condition, 400 values were processed based on the penetration depth. The data underwent statistical analysis, with emphasis on their distribution in quartiles. To address the inherent punctual extreme variability in agricultural soil, the penetration resistance curves were constructed by incorporating the resulting mean values. Figure 2 provides an illustrative example of a typical data distribution. To mitigate potential interference, samples were

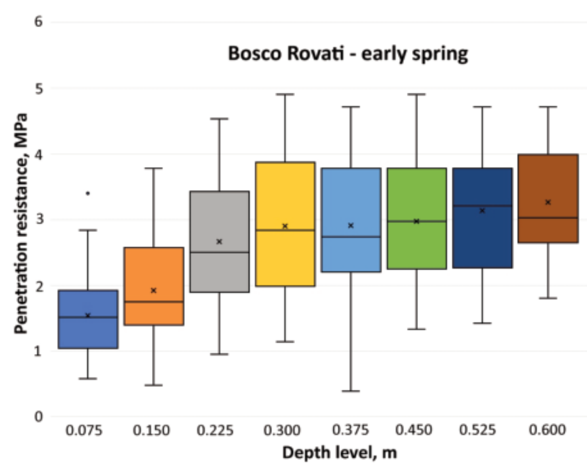

Figure 2. Illustrative example of the data distribution undertaken for each investigated condition.

Table 1. Scenarios considered for the study of soil compaction throughout the entire growing season in the surveyed vineyards.

Campaign period	Passes of the machinery into the vineyard, no.	Operation	Sampling point
Early spring (mid April)	--	--	Row
Early summer (mid July)	8	PPP spraying, grass shredding	Centre of
End of summer (mid September)	1	PPP spraying	inter-row
Early autumn (beginning of October)	1	Mechanical harvesting (San Michele vineyard only)	Ruts

PPP, plants protection products.

probed at a minimum distance of 2 m from each other within the row, at the centre of the inter-row, and in the ruts (Figure 3). The water content of the soil significantly influences its susceptibility to compaction under the influence of machinery traffic. To comprehensively explore this correlation, soil samples were collected at depths of 0.1 and 0.3 m throughout the entire growing season. These specific depth values were selected to assess: i) at 0.1 m, the sensitivity of the topsoil to compaction, as it represents the layer most affected by machinery traffic, and ii) at 0.3 m, because this level is widely recognized as the transition between the topsoil and the subsoil (Figure 4). The calculation of gravimetric moisture content was conducted using the «dry basis» as a reference, following the formula:

$$\text{moisture content (\%)} = \frac{\text{(initial soil mass - dry soil mass)}}{\text{dry soil mass}} \cdot 100$$

The measurement of soil penetration resistance was conducted using a hand-operated electronic penetrometer equipped with a 30° inclination cone with a total base area of 1 cm², adhering to the specifications outlined in ASAE S313.3 and ASAE EP542. The penetrometer, manufactured by Eijkelkamp (Giesbeek, Netherlands) and designated as the Penetrologger model, comprises an interchangeable tip measuring needle, a load cell (for force detection), an ultrasonic sensor (for measuring penetration depth), and a set of electronics that includes a microprocessor, a GPS module, a memory module, and a battery.

The experimental protocol encompassed distinct objectives to be investigated in each vineyard:

- in the Bosco vineyard, the focus was on examining the compaction trend throughout the entire growing season at each surveyed location;
- in the Bosco Rovati vineyard, a comparative analysis was conducted between tilled and grassed inter-rows, considering both the centre of the inter-row and the ruts as an average. Resistance to compaction was measured in early spring, at the onset of the growing season and before any machinery traffic, to account for the natural regeneration of the soil structure during the cold season;
- in the San Michele vineyard, soil compaction was similarly measured at the beginning of the growing season, with a comparison across different locations (row, centre of the inter-row, and ruts). This assessment considered the potential increase in compaction resulting from the previous season's mechanical harvesting, carried out with a towed grape harvester.

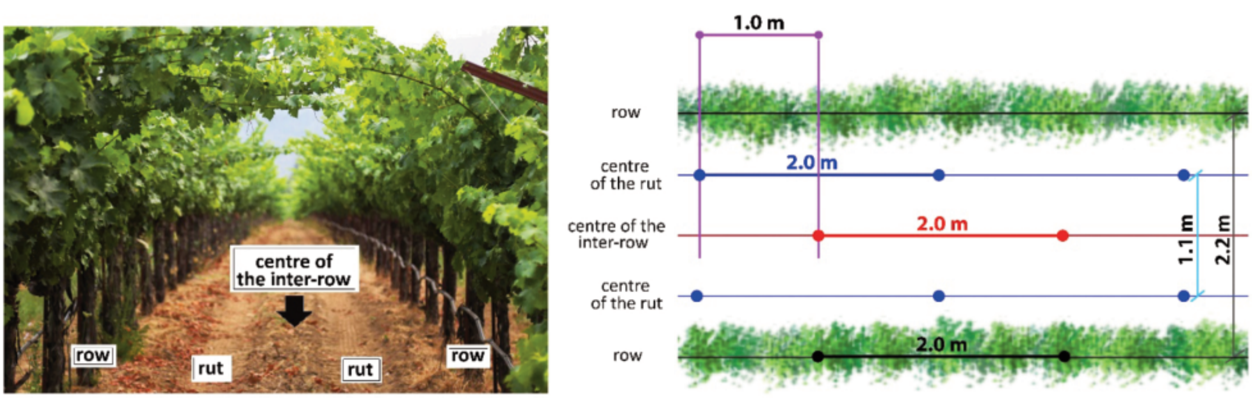

Figure 3. Overview of locations (left) and diagram (right) depicting the penetration points.

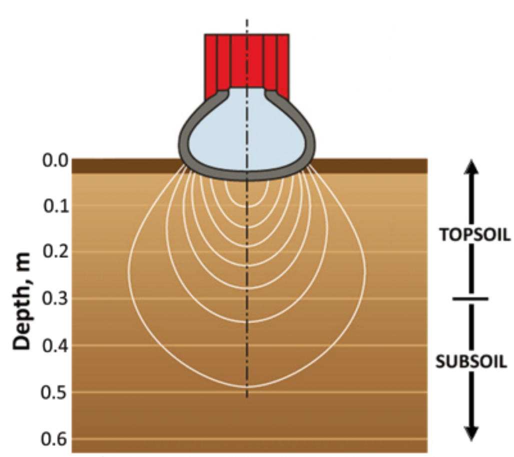

Figure 4. The uppermost layer of the topsoil is particularly sensitive to compaction caused by machinery traffic, while the 0.3 m depth is widely recognized as the transition point between the topsoil and subsoil.

Results and Discussion

Due to its significant influence, particularly in the topsoil, the compaction results were examined in connection with the rainfall and air temperature prevalent during the corresponding period. This analysis pertains to a weather station located in close proximity (7 km away) to the surveyed vineyards. Notably, three distinct periods of substantial rainfall were recorded: the end of April to the beginning of May, the latter half of July, and the initial half of September (Figure 5 a,b). Table 2 displays the soil moisture con-

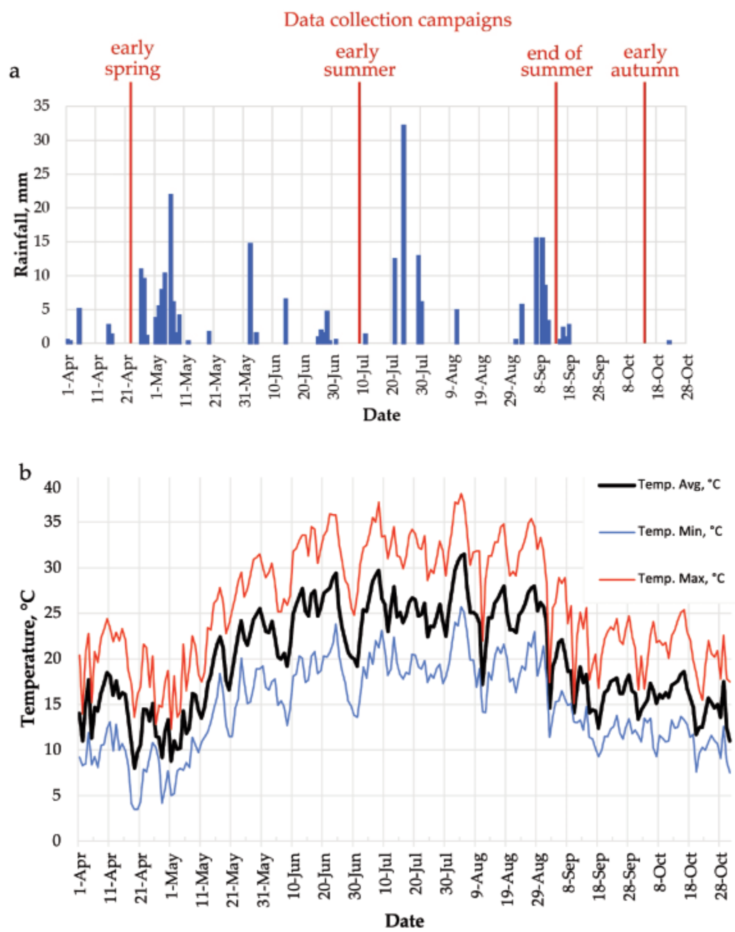

Figure 5. a) Rainfall documented throughout the testing season and dates of the data collection campaigns. **b**) Air temperature documented throughout the testing season.

Table 2. Gravimetric soil moisture content values at 0.1 and 0.3 m depth of the surveyed vineyards, in different periods of the growing season.

Vineyard	Period	Gravimetric moisture content, % Depth 0.1 m	Depth 0.3 m
Bosco	Early spring	5.3	16.3
	Early summer	8.9	11.7
	End of summer	16.0	8.9
	Early autumn	11.6	13.3
Bosco Rovati (grassed)	Early spring	9.9	13.6
	Early summer	9.1	11.1
	End of summer	13.5	7.9
	Early autumn	11.7	12.7
Bosco Rovati (tilled)	Early spring	4.4	13.0
	Early summer	5.4	7.8
	End of summer	4.7	5.4
	Early autumn	8.8	10.3
San Michele	Early spring	6.4	14.9
	Early summer	7.9	10.3
	End of summer	16.7	10.4
	Early autumn	12.7	14.3

tent values at depths of 0.10 and 0.30 m for the surveyed vineyards.

Throughout the entire growing season, the gravimetric moisture content ranged from 4.4% to 16.3%. These values have the potential to form layers of dry and high-resistance soil, especially considering that the vineyard textures were loamy-silty and loamy-clayey. The moisture content is higher at a depth of 0.3 m compared to 0.1 m, with notable differences in early spring; this difference tends to decrease in early autumn. An exception was observed at the end of summer when, in the Bosco, Bosco Rovati (grassed), and San Michele vineyards, the moisture content was higher in the upper layer. This anomaly is likely attributed to a preceding period of intense rainfall occurring between late August and early September, specifically on August 31 and September 2, 7, 9, and 10. This is corroborated by Unger and Kaspar (1994), who noted that while compaction may restrict root growth, fluctuations in weather conditions can either exacerbate or mitigate the impact of root limitation on crop growth.

The comparison between the two inter-row soil management solutions (grassed or tilled) generally indicates a superior performance of the grassed solution, exhibiting significantly higher moisture content than the tilled inter-rows within the same vineyard. Despite a preceding period of heavy rainfall, the tilled soil displayed markedly low moisture content at both 0.1 and 0.3 m depths, likely attributed to intense evapotranspiration induced by the high temperatures during that period.

Regarding penetration resistance, Figure 6 depicts the results obtained in the Bosco vineyard. In the row, the penetration resistance demonstrates an increase throughout the growing season, confirming that machinery traffic affects the compaction of the soil even beyond the immediate vicinity of wheel or track passes. In fact, the location and above all the extent of machinery traffic-induced compaction are results of a complex interplay of intrinsic soil properties, field conditions under which trafficking takes place, and the specifications of employed machinery (Bengough *et al*., 2011). Within the first 0.1 m, penetration resistance experiences rapid initial growth but remains relatively constant, reaching approximately 1.6 MPa over the season. At greater depths, values worsen as the season progresses, culminating in critical values in late summer to early autumn. The observed trend of increasing values during the season is consistent in the center inter-row as well. At a depth of 0.1 m, penetration resistance is approximately 2.5-2.8 MPa, escalating to 4.5 MPa at depths of 0.4-0.6 m, consistently observed in late summer and early autumn (Figure 7).

In accordance with expectations, the most challenging conditions were observed in the ruts. The average compaction within the two ruts displayed elevated values, closely approaching or even surpassing 4 MPa at depths less than 0.1 m during various test periods. Additionally, penetration resistance remained consistently between 4 and 5 MPa at greater depths (Figure 8).

The tests conducted in the Bosco Rovati vineyard during early spring, aimed at determining the impact of inter-row management on soil compaction without the interference of machinery traffic, confirmed the expected superior performance of the tilled soil. This superiority was evident both in the center inter-row and, more prominently, in the ruts (Figures 9 and 10).

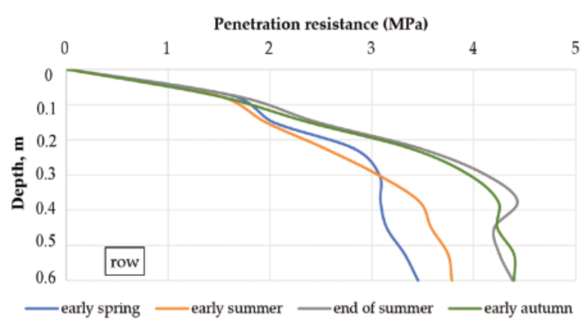

Figure 6. Penetration resistance curves recorded in the row for four periods along the growing season in the Bosco vineyard.

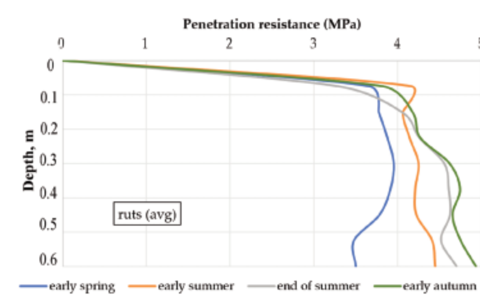

Figure 8. Penetration resistance curves recorded in the ruts (average) for four periods during the growing season in Bosco vineyard.

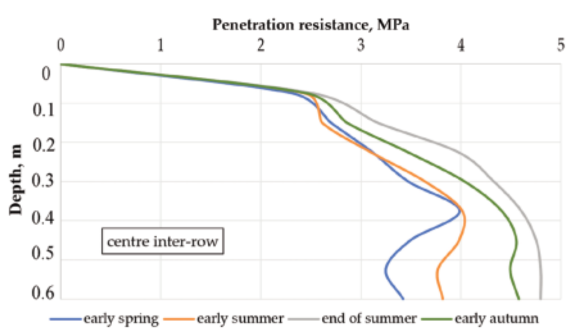

Figure 7. Penetration resistance curves recorded in the centre inter-row for four periods during the growing season in Bosco vineyard.

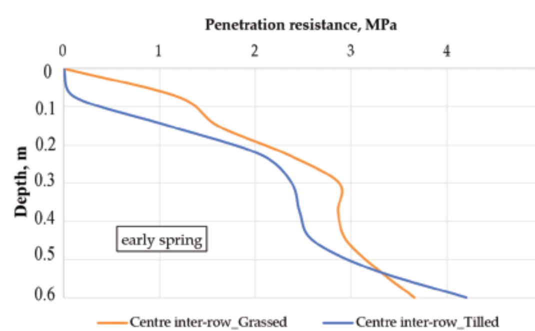

Figure 9. Penetration resistance curves recorded in the centre inter-row tilled or grassed in Bosco Rovati vineyard.

The soil compaction in areas managed under the two systems (grassed and tilled in Bosco Rovati vineyard) reveals notable distinctions. A consistent contrast is evident at the center of the inter-row, while in the ruts, the differences are more pronounced: at a depth of 0.1 m, the resistance values in the grassed rows are nearly 3 MPa higher than those in the tilled rows. This contrast remains significant (approximately 1.5 MPa) up to a depth of about 0.55 m, beyond which the values tend to converge. The observed variation can be attributed to the impact of tillage. In San Michele vineyard, harvesting was conducted using a towed grape harvester in the preceding season. Compaction tests were performed at the onset of the growing season at various points, to assess the detrimental effects of grape harvester traffic (Figure 11).

Two factors can exacerbate soil conditions during mechanical harvesting: the machine's high overall mass (periodically increased when travelling with full tanks) and the necessity to harvest at a specific time of the season when the vine has attained the required ripeness level, even if the soil might be wet, rendering it highly susceptible to compaction. Moreover, the grape harvester, being a straddle machine, travels the vineyard with the left side two wheels in one inter-row and the other two on the right side in the next. Due to its typical track width, the ruts created by the grape harvester correspond to those generated by regular machinery traffic, further aggravating compaction in those areas.

In this vineyard, to validate the effectiveness of soil structure regeneration during the cold season, the compaction level in the row does not exceed 2 MPa up to approximately 0.5 m deep. However, although the tests were conducted at the beginning of the subsequent season, a few months after harvest, thus encompassing the soil regeneration period, the results in the centre of the inter-row and in the ruts unfortunately confirmed the expected outcome - that is, compaction levels are significantly impacted by the grape harvester traffic. Specifically, in the ruts penetration resistance exceeds 4.5 MPa at depths of less than 0.1 m, while at greater depths, the values rapidly decrease, reaching less than 3 MPa from around 0.4 to 0.6 m. In the center of the inter-row, penetration resistance is at an intermediate level between the two aforementioned areas, swiftly escalating to almost 3 MPa in the first 0.1 m of depth.

In general, the observed scenario in the investigated vineyards appears to be notably critical when juxtaposed with analogous studies. A study conducted by Van Huyssteen (1983) in South Africa evaluated soil compaction at various points and depths within vineyard inter-rows, subjected to diverse tillage systems. This investigation revealed maximum penetrometer resistance values ranging from 0.6 to 2.8 MPa. Significant variations in critical soil compaction values, contingent on vine vigour, have been identified in other vineyard studies, ranging from 1 to 3 MPa (Lanyon *et al*., 2004). Conversely, Quezada *et al*. (2014) established a critical threshold at 2 MPa under field capacity conditions.

Bengough *et al*. (2011) carried out a literature review on relationships between root elongation rate, water stress (matric potential), and mechanical impedance (penetration resistance). They found that root elongation is typically halved in repacked soils with penetrometer resistances >0.8-2 MPa, in the absence of water stress. Moreover, they concluded that mechanical impedance is often a major limitation to root elongation in these soils even under moderately wet conditions. Focusing specifically on the influence of progressively intensifying machinery traffic, Carrara *et al*. (2005) documented cone penetrometer resistance values under open field conditions. Undisturbed soil exhibited values ranging from 0.08 to 1.43 MPa, while after a single tractor pass, the range extended from 0.20 to 1.47 MPa. Subsequent to four passes, the values increased to a range of 0.22 to 1.51 MPa. This information underscores the severity of soil compaction resulting from machinery operations in vineyards, emphasizing the need for careful consideration of tillage practices and machinery management to mitigate adverse effects on soil structure and health.

In this critical scenario, the rut surface appears impermeable to rain. In the event of heavy rainfall, particularly if the vineyard rows are aligned along the line of maximum slope, there is a substantial risk of intense runoff, leading to erosion and the transport of a significant amount of sediment. This risk is substantiated by the rainfall data recorded during the test season (Figure 3a), indicating a high probability of heavy rainfall in early spring in Northern Italy. Conversely, in the centre of the inter-row and especially in the row, rain can promptly and deeply permeate the soil, thereby averting (or at least minimizing) surface erosion. To ameliorate the situation, various measures can be implemented, primarily focusing on agronomic practices. Periodic tillage, such as harrowing, hoeing or spading, along with the use of a cultivator (up to a maximum depth of 0.2 m), prove beneficial in restoring the proper physical structure of the topsoil. This observation aligns with the findings reported by Ozpinar *et al*. (2018), who conducted a study examining the impact of tillage practices on various soil parameters, including penetration resistance, within vineyards in Turkey. Their findings revealed that the highest penetration resistance values (ranging from 1.65 to 2.61 MPa) were consistently observed below the till-

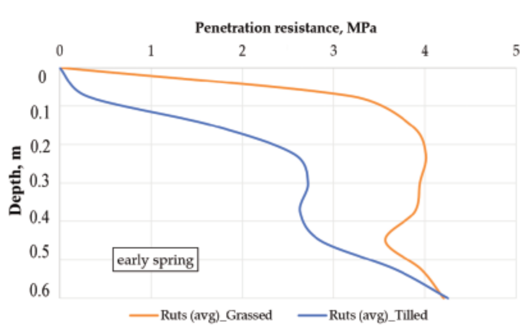

Figure 10. Penetration resistance curves recorded in the ruts (average) tilled or grassed in Bosco Rovati vineyard.

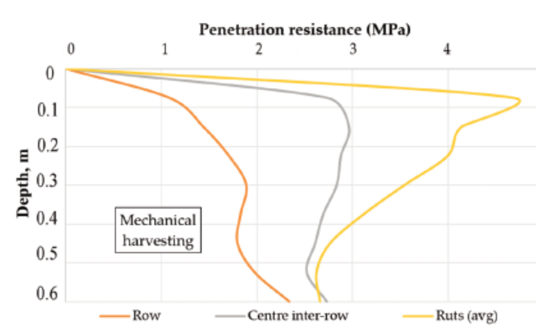

Figure 11. Penetration resistance curves for different sampling points in a vineyard where mechanical harvesting was carried out in San Michele vineyard.

ing depth (20 cm), irrespective of the tillage systems employed. Specifically, they noted that penetration resistance was elevated in the subsoil of inter-rows following the use of a hand-driven rotary tiller compared to tillage performed with a tractor-mounted rotary tiller or a field cultivator. Additionally, the lowest penetration resistance values were recorded in the subsoil when utilizing the field cultivator.

Attention must be paid in case the vineyard rows are planted in the direction of the maximum slope, to avoid soil erosion and significant sediment transport. Diversely, permanent grassing is effective in reducing runoff and evapotranspiration. However, it's essential to manage grass growth periodically, as it can compete with vines for nutrient uptake. Hybrid approaches, involving alternating grassy and tilled inter-rows in the vineyard or varying the inter-row management in subsequent growing seasons, have proved recently good results, minimizing drawbacks (Bordoni *et al*., 2019; Capello *et al*., 2019).

On the other hand, it is crucial to consider also the subsoil structure: deep tillage methods such as chiseling or ripping should be employed intermittently, approximately every 3, 5, or 7 years, depending on the severity of subsoil compaction. Care should be taken during deep tillage to disturb the soil of the row as little as possible, preserving the integrity of the plant's root system (Coulouma *et al*., 2006). Organic fertilization solutions, such as manure, solid digestate and compost distribution not only enhance the nutritional potential but also ameliorate the soil physical structure, thanks to the addition of a significant amount of organic matter (Jakšić *et al*., 2021). Furthermore, the incorporation of green manure in the inter-rows contributes organic matter, enhancing soil health (Dobrei *et al*., 2016). This improvement extends to both the physical and chemical characteristics of the soil, thereby positively impacting the quality and quantity of vine and wine by-products. Legume mixes are frequently adopted practices, also to boost nitrogen's nutritional potential.

Regarding mechanization, several strategies can be implemented to mitigate soil compaction (Biddoccu *et al*., 2020; Pessina *et al*., 2021). Reducing the overall mass of machines and their frequency of passage in the vineyard can yield benefits for both the soil and, notably, the subsoil. In particular, a reduction in the frequency of PPP applications throughout the growing season can also provide a significant advantage.

A further opportunity to mitigate compaction, notably when it is localized in the ruts, involves the adoption of wide-section and low inflation pressure tyres, thereby increasing their contact area and reducing the average ground pressure (Pessina *et al*., 2021). Nevertheless, caution must be exercised due to the potential constraint posed by the increased overall width of the tractors and the narrow inter-row spaces in vineyards. Conversely, the employment of crawler tractors could offer substantial benefits owing to the extensive contact area of their tracks. However, this option is not always advisable due to limited mobility, a lower level of comfort and the potential for surface damage in grassy vineyards.

Conclusions

For vineyard, researchers often cite a penetration resistance limit of 1-3 MPa, beyond which issues affecting vine development occur, negatively impacting overall plant health and increasing susceptibility to pathogens. In the present investigation, values significantly exceeding this range were consistently observed, with readings reaching or surpassing 4 MPa in the surface layer of the ruts. These critical values were not only encountered during prolonged periods of drought but also occasionally within the topsoil during early spring, coinciding with the onset of the growing season. On the other hand, soil texture and rainfall, being beyond human manipulation, pose inherent challenges. Despite the natural soil regeneration occurring during the cold season, compaction tends to exacerbate throughout the season.

This phenomenon is not only evident in the ruts and in the inter-row areas, but also extends along the row, particularly in the subsoil (below 0.3 m). In the latter half of the growing season, the penetration resistance values recorded frequently surpassed 4 MPa in this zone. This observation confirms that the detrimental effects of compaction are not confined to specific localized regions but rather permeate the entire vineyard area.

Given the limited potential for natural regeneration of intensely cultivated soils, successful mitigation of soil compaction in vineyards relies solely on the careful and sustainable implementation of various agronomic and mechanized cultivation methods. Moreover, for soils highly susceptible to compaction, routine tillage, encompassing both shallow and deep techniques, may prove essential to enhance their physical structure and restoring favorable conditions for the development of the vine root system.

References

Arnaez, J., Lasanta, T., Ruiz-Flaño, P., Ortigosa, L. 2007. Factors affecting runoff and erosion under simulated rainfall in Mediterranean vineyards. Soil Till. Res. 93:324-34.

Bengough, A.G., McKenzie, B.M., Hallett, P.D., Valentine, T.A., 2011. Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. J. Exp. Bot. 62:59-68.

Biddoccu, M., Capello, G., Cavallo, E. 2020. Effects of tractor traffic on soil compaction, water infiltration and soil erosion in tilled and grassed vineyards. EGU General Assembly, Online, EGU2020-10352.

Biddoccu, M., Ferraris, S., Opsi, F., Cavallo, E. 2016. Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North-West Italy). Soil Till. Res. 155:176-89.

Bogunovic, I., Bilandzija, D., Andabaka, Z., Stupic, D., Comino, J.R., Cacic, M., et al. 2017. Soil compaction under different management practices in a Croatian vineyard. Arab. J. Geosci. 10:340

Bogunovic, I., Kisic, I., Maletic, E., Jurisic, A., Roskar, L., Dekemati, I. 2016. Soil compaction in different ages vineyards in Pannonian Croatia. Part II. Modeling spatial variability of soil compaction parameters in vineyard. J. Cent. Eur. Agric. 17:545-62.

Bogunovic, I., Kisic, I., Maletic, E., Perčin, A., Matošić, S., Roskar L. 2016. Soil compaction in vineyards of different ages in Pannonian Croatia. Part I. Influence of machinery traffic and soil management on compaction of individual horizons. J. Cent. Eur. Agric. 17:533-44.

Bordoni, M., Vercesi, A., Maerker, M., Ganimede, C., Reguzzi, M.C., Capelli, E., et al. 2019. Effects of vineyard soil management on the characteristics of soils and roots in the lower Oltrepò Apennines (Lombardy, Italy). Sci. Total Environ. 693:133390.

Burg, P., Zemánek, P., Turan, J., Findura, P., 2012. The penetration resistance as a soil degradation indicator in the viticulture. Acta Univ. Agric. Silvic. Mendel. Brun. 60:29-36.

Capello, G., Biddoccu, M., Ferraris, S., Cavallo, E. 2019. Effects of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards. Water (Basel) 11:2118.

Capello, G., Biddoccu, M., Cavallo, E., 2020. Permanent cover for soil and water conservation in mechanized vineyards: A study case in Piedmont, NW Italy. It. J. Agron. 15:323-31.

Carrara, M., Comparetti, A., Febo, P., Orlando, S., 2005. Sistemi per la valutazione del compattamento dei terreni agrari. Proceedings Nat. Conf. AIIA 2005 "L'ingegneria agraria per lo sviluppo sostenibile dell'area mediterranea", Catania.

Coulouma, G., Boizard, H., Trotoux, G., Lagacherie, P., Richard, G., 2006. Effect of deep tillage for vineyard establishment on soil structure: A case study in Southern France. Soil Till. Res. 88:132-43.

Davies, S., Bakker, D., Lemon, J. 2018. The science of soil compaction. Available from: https://www.agric.wa.gov.au/soil-compaction/science-soil-compaction

Dobrei, A., Alina, D., Nistor, E., Camen, D., Sala, F., 2016. Improvement of soil physical and chemical properties with green manure for healthy vine and wine by-products. Proceedings International Multidisciplinary Scientific GeoConference: SGEM. Sofia. pp. 157-64.

Ferianc, J., Badalíková, B., Burg, P., Burgová J., 2016. The monitoring of soil properties in the interrow of vineyards. Acta Univ. Agric. Silvic. Mendel. Brun. 64:417-22.

Ferree, D.C., Streeter, J.G., 2004. Response of container-grown grapevines to soil compaction. HortScience 39:950-954.

Ferrero, A., Usowicz, B., Lipiec, J., 2005. Effects of tractor traffic on spatial variability of soil strength and water content in grass covered and cultivated sloping vineyard. Soil Till. Res. 84:127-38.

Jakšić, S., Ninkov, J., Milić, S., Vasin, J., Banjac, D., Jakšić, D., Živanov, M., 2021. The state of soil organic carbon in vineyards as affected by soil types and fertilization strategies (Tri Morave Region, Serbia). Agronomy (Basel) 11:9.

Kvaternjak, I., Kisić, I., Špoljar, A., Kamenjak, D., Jelen, R., 2012. Mechanical resistance of soil in selected vineyards of different ages in Križevci area. Proceedings 47th Croatian and 7th Int. Symp. on Agriculture, Opatija. Available from: https://www.yumpu.com/en/document/read/19117443/47th-croatian-and-7th-international-symposium-on-agriculture-#google_vignette

Lagacherie, P., Coulouma, G., Ariagno, P., Virat, P., Boizard, H., Richard, G., 2006. Spatial variability of soil compaction over a vineyard region in relation with soils and cultivation operations. Geoderma 134:207-16.

Lamandé, M., Schjønning, P., 2011. Transmission of vertical stress in a real soil profile. Part III: Effect of soil water content. Soil Till. Res. 114:78-85.

Lanyon, D.M., Cass, A., Hansen, D., 2004. The effect of soil properties on vine performance. CSIRO Land and Water, Technical Report 34/04. Available from: https://publications.csiro.au/publications/publication/PIprocite:f30fdf05-8bbc-40b8-a332-51172ba6d625

Lazcano, C., Decock, C., Wilson, S.G., 2020. Defining and managing for healthy vineyard soils, intersections with the concept of terroir. Front. Environ. Sci. 8:68.

Liebhard, G., Winter, S., Zaller, J. G., Bauer, T., Fantappiè, M., Strauss, P., 2024. Effects of vineyard inter-row management on soil physical properties and organic carbon in Central European vineyards. Soil Use Manage. 40:e13101.

Linares, R., de la Fuente, M., Junquera, P., Lissarrague, J.R., Baeza, P., 2014. Effects of soil management in vineyard on soil physical and chemical characteristics. BIO Web of Conferences 3:01008.

Martínez-Casasnovas, J.A., Concepcion Ramos, M., 2009. Soil alteration due to erosion, ploughing and levelling of vineyards in north east Spain. Soil Use Manage. 25:183-92.

Morlat, R., Jacquet, A., 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. Am. J. Enol. Vitic. 54:1-7.

Napoli, M., Dalla Marta, A., Zanchi, C.A., Orlandini, S., 2017. Assessment of soil and nutrient losses by runoff under different soil management practices in an Italian hilly vineyard. Soil Till. Res. 168:71-80.

Nawaz, M., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron. Sustain. Dev. 33:291-309.

Ozpinar ,S., Ozpinar, A., Cay, A. 2018. Soil management effect on soil properties in traditional and mechanized vineyards under a semiarid Mediterranean environment. Soil Till. Res. 178:198-208

Pessina, D., Galli, L.E., Santoro, S., Facchinetti, D., 2021. Sustainability of machinery traffic in vineyard. Sustainability (Basel) 13:2475.

Polge de Combret-Champart, L., Guilpart N., Mérot A., Capillon A., Gary C., 2013. Determinants of the degradation of soil structure in vineyards with a view to conversion to organic farming. Soil Use Manage. 29:557-66.

Quezada, C., Soriano, M.A., Díaz, J., Merino, R., Chandía, A., Campos, A., Sandoval, M., 2014. Influence of soil physical properties on grapevine yield and maturity components in an Ultic Palexeralf soils, Central-Southern, Chile. Open J. Soil Sci. 4:127-35.

Rodrigo-Comino, J., 2018. Five decades of soil erosion research in "terroir". The State-of-the-Art. Earth-Sci. Rev. 179:436-47.

Schneider, M.A., Stanier, S.A., White, D.J., Randolph, M.F., 2020. Shallow penetrometer tests: theoretical and experimental modelling of penetration and dissipation stages. Can. Geotech. J. 57:568-79.

Špoljar, A., Kvaternjak, I., Slunjski, D., 2014. Mechanical resistance of soil in vineyards of different ages. Agronomski glasnik 76:267-76.

Unger, P.W., Kaspar, T.C., 1994. Soil compaction and root growth: a review. Agron. J. 86:759-66.

Van Huyssteen, L., 1983. Interpretation and use of penetrometer data to describe soil compaction in vineyards. South Afr. J. Enol. Vitic. 4:2371.

Visconti, F., López, R., Olego, M.Á., 2024. The health of vineyard soils: towards a sustainable viticulture. Horticulturae 10:154.

Wang, D.Y., Tang, C.S., Cui, Y.J., Shi, B., Li, J., 2016. Effects of wetting-drying cycles on soil strength profile of a silty clay in micro-penetrometer tests. Eng. Geol. 206:60-70.

Wheaton, A.D., McKenzie, B.M., Tisdall, J.M., 2008. Management to increase the depth of soft soil improves soil conditions and grapevine performance in an irrigated vineyard. Soil Till. Res. 98:68-80.